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Impact of sea-level rise on the tourist-carrying capacity of Catalan beaches

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ABSTRACT

Tourism provides about 11% of Catalonia's GDP, with most accommodations placed being associated with the "sun-and-sand" model. Since beaches are the main resource to be exploited, it is important to assess how their future evolution can affect this economic sector. Accordingly, we present a methodology to assess the effect of shoreline evolution on beach recreational carrying capacity (BCC) at different territorial scales considering different climate change scenarios. Our results suggest that by 2050, in the absence of climate change, tourist BCC will decrease down to 83% of current values due to the dominant erosive behaviour of the Catalan coast. When sea-level rise is considered, BCC will decrease further, with expected values ranging from 74% to 53% of current capacity for the tested scenarios (RCP4.5 and High-end respectively). Hence, current erosional trends are adverse for future development of coastal tourism in Catalonia, and accelerated sea-level rise exacerbates this adverse situation. The adopted methodology permits to locate hotspots along the territory where local BCC values collapse as well as to predict when this will occur under a given climatic scenario. Moreover, the use of different spatial scales to integrate BCC permits to test management strategies to sustaining the recreational use of beaches.

1. Introduction

It is well known that coastal areas are associated with large and growing concentrations of population, increasing urbanization and socioeconomic activities, which cause interactions between human uses and natural processes. Small and Nicholls (2003) estimated that 23% of the global population lives within 100 km of a shoreline and less than 100 m above sea level. The population density in these near-coastal areas is nearly three times higher than the worldwide average density. These areas also exhibit high rates of population growth (Neumann et al., 2015), and show a high susceptibility to change due to the accumulation of human-induced pressures (e.g., Newton et al., 2012).

Tourism has become one of the main economic engines of coastal areas worldwide. The Mediterranean is the world's leading tourist destination, accounting for about 30% of international tourism globally, with about half of tourist arrivals being in the coastal zone, mainly during the summer season (Plan Bleu, 2016). The majority of coastal tourism is based on the sun-and-sand model and, as consequence; beaches become one of the main resources in providing economic and social values (e.g., Houston, 2013). Within this context, preserving or enhancing beach quality is one of the main goals of coastal managers in maintaining and/or promoting the attractiveness of beaches for tourists and visitors (e.g., Fraguell et al., 2016). One of the main elements in controlling the quality of a beach from a recreational standpoint is the available space for users, which is usually referred to as the physical-carrying capacity (Table 1 shows the main definitions and terminology used in this work). In this sense, any meaningful planning of a sun-and-sand destination needs to include a proper assessment of the carrying capacity of existing beaches, which will define the number of users to be accommodated as well as their level of comfort (e.g., De Ruyck et al., 1997; Pereira da Silva, 2002; Valdemoro and Jiménez, 2006). Thus, there is no doubt that the formulation of any sustainable, long-term planning of coastal tourism must include the potential effects of climate change on the quality of resources to be exploited (Hamilton et al., 2005; Moreno and Amelung, 2009a). Among the different climate change-induced impacts, Moreno and Amelung (2009a) concluded that sea level rise (SLR) and/or water availability will be key factors potentially affecting coastal tourism on Mediterranean coasts. With respect to beach quality, SLR will be main source of risk with shoreline retreat and inundation being the most important induced impacts on sandy coastlines (e.g., Nicholls and Cazenave, 2010). Since beach dimensions determine the available surface area for users and services to be provided, morphodynamic processes will condition beach use and exploitation (Valdemoro and Jiménez, 2006). Hence, this work focuses on the potential impacts of SLR-induced shoreline retreat on coastal tourism.

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Table 1
Key parameter terminology and definitions.

Carrying Capacity	Amount and type of visitors that can be accommodated within a given amenity area without unacceptable social consequences and without a negative impact on resources (Clark, 1996; Manning and Lawson, 2002; WTO, 1997).
Minimum area per user	Bearable beach surface area per user value without affecting the user-recreational experience. It depends on the beach type and use intensity.
Resting area (also termed “used beach surface” within the text)	Area where most beach users stay and consequently, where umbrellas and sunbeds are usually placed. Beach services are usually located landward of this area unless the beach is too narrow.
Physical-Carrying Capacity (PCC)	Maximum number of users that can physically be accommodated on a beach. It depends on beach dimensions, resting area, and minimum area per user.
Tourist BCC	PCC integrated to a given territorial unit for specific potential users (tourists).

Within the Mediterranean, Spain is a traditional sun-and-sand destination where coastal municipalities have experienced an intense urban and touristic development. According to the Spanish Institute of Statistics, about 26% of foreign tourists visiting Spain chose Catalonia as their destination in 2015. With the exception of the city of Barcelona, the majority of the tourism industry is based on the sun-and-sand model where coastal destinations comprise more than 62% of tourism overnights. (Generalitat de Catalunya, 2015). Hence beaches are the main asset of this economic sector (Rigall-i-Torrent et al., 2011). To this end, we assess the recreational carrying capacity of beaches to accommodate the tourist demand using tourist beach carrying capacity (tourist BCC, see Table 1 for definitions).

Within this context, the main aim of this paper is to assess the potential impact of SLR on the recreational carrying capacity of Catalan beaches and hence the potential influence on the sun-and-sand tourism economic model over the coming decades. This is accomplished via three objectives: (1) developing a model of recreational beach utilisation appropriate for Catalonia; (2) developing a shoreline evolution-beach use interaction model; and (3) forecasting the resulting evolution of tourist BCC along the Catalan coast under different SLR scenarios. The practical goal of this research is to support coastal managers in the decision-making process by defining the appropriate mitigation/adaptation measures required for long-term coastal tourism planning.

2. Study area and data

2.1. Study area

The Catalan coast is located in the NE Spanish Mediterranean (Fig. 1). Its 600 km-long coastline comprises a large diversity of coastal types, ranging from cliffs to low-lying areas; with about 270 km of beaches. Currently, more than 60% of the beaches along the Catalan coast are impacted by erosion (CIIRC, 2010).

The Catalan coast comprises 70 municipalities and 12 *comarcas* (territorial units comparable to counties) (Fig. 1). These *comarcas* comprise about 23% of the territory of Catalonia and 62% of the total population (IDESCAT, 2016). The economy is based on activities such as tourism, commerce, agriculture, and residential development (Sardá et al., 2005). Tourism is one of the main economic sectors providing about 11% of the Catalan GDP (Duro and Rodríguez, 2011), with most accommodations being associated with three tourism brands located along the coast; *i.e.,* Costa Brava, Costa Dorada, and Costa de Barcelona (Generalitat de Catalunya, 2015) (See Fig. 2).

Due to its uniqueness within the Catalan coast, the Ebro Delta has been excluded from the current analysis. The delta is intensively used for agriculture, and it comprises important natural resources, which are protected under Natural Park protection laws. Thus, in spite of having more than 50 km of beaches, their recreational use is secondary, with most visits being nature-oriented (Rodríguez Santalla, 2004; Romagosa and Pons, 2017). Due to this, and to avoid the distortion of the analysis from the large delta beach area on the assessment of the regional carrying capacity, we have left out their potential contribution which deserves a specific analysis.

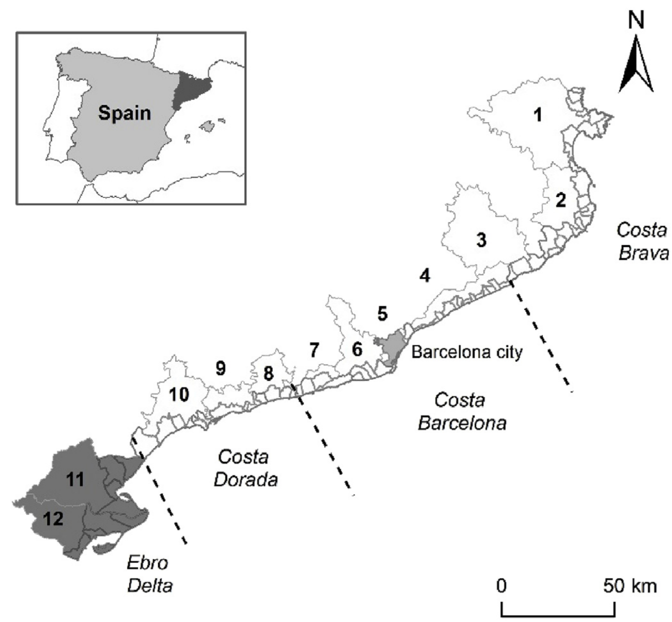

Fig. 1. The Catalan coast divided into tourism coastal brands (names in italics) and 12 administrative units (comarcas) (from North to South; 1: Alt Empordà; 2: Baix Empordà; 3: Selva; 4: Maresme; 5: Barcelonés; 6: Baix Llobregat; 7: Garraf; 8: Baix Penedés; 9: Tarragonés; 10: Baix Camp; 11: Baix Ebre; 12: Montsià). The smaller divisions within each comarca correspond to the 70 coastal municipalities. Note: Comarcas 11 and 12 were excluded from the analysis.

2.2. Data

The data used in this work can be grouped into three types: (1) beach information, including the geomorphology, typology, and intensity of use; (2) socio-economic information related to beach demand; and (3) SLR projections.

2.2.1. Beach data

Beach data are used to estimate shoreline dynamics and to characterize beach morphology and typology. In order to assess beach evolution under current climate conditions, we have used a collection of aerial photographs covering the entire Catalan coast taken in 10 flight surveys during the period from 1995 to 2015 by the Cartographic and Geologic Institute of Catalonia (ICGC). These photos are taken at a scale 1:2500 and have a mean square error smaller than 0.5 m. To characterize current beach characteristics (width, length, and degree of urbanization of the hinterland) we have used the most recent available aerial photograph (2015).

Beaches were classified in terms of the degree of urbanization and in terms of their intensity of use. To this end, in addition to the above-mentioned set of aerial photographs, we used information provided by two public databases: (i) the Beach Guide of the Spanish Ministry of Agriculture, Fish, Food, and Environment (MAPAMA), and (ii) the beach database of the Catalan Government (Generalitat de Catalunya,

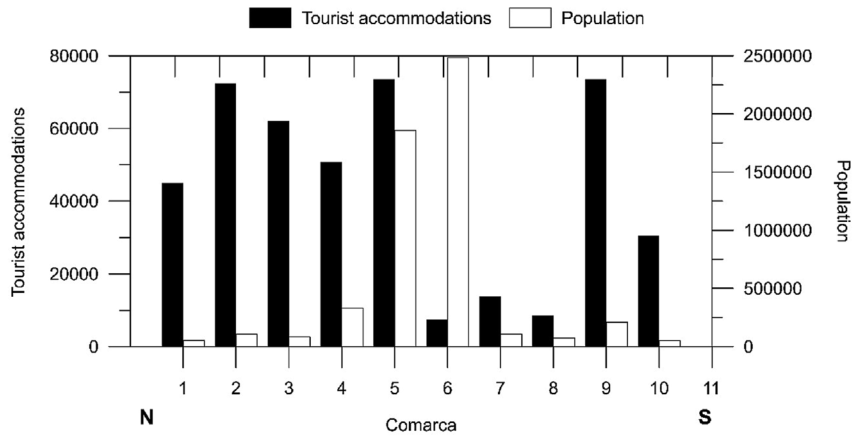

Fig. 2. Tourist accommodation (bed places) and population values for each comarca along the Catalan coast (see comarcas in Fig. 1). Note: Comarcas 11 and 12 were excluded from the analysis.

Table 2
Beach typology and minimum area per user associated with their intensity of use.

Beach typology	Characteristics	Intensity of use	Minimum area per user (m^2/user)
Urban	Within the main nucleus of a given municipality. > 60% urbanized hinterland.	high	4
Semi-urban	In residential areas outside the main nucleus of a municipality. 30–60% urbanized hinterland.	high	4
		moderate	8
		low	12
Rural	Outside the main nucleus of a municipality. < 30% urbanized hinterland and uninhabited areas.	high	4
		moderate	8
		low	12

2016). Hence, beaches were classified into three categories according to the degree of urban development of the hinterland: (1) urban, (2) semi-urban and (3) rural (see e.g., Ariza et al., 2008); and into three sub-categories based on typical intensity of use during the bathing season: (1) high, (2) moderate and (3) low. Each beach category was assigned a minimum area per user (Table 2). This value determines the use saturation level and it depends on the beach type, having a low value of 4 m^2/user for urban, highly-frequented beaches (see Alemany, 1984; PAP, 1997; Roca et al., 2008; Valdemoro and Jiménez, 2006; Yepes, 1999).

2.2.2. Potential beach-user data

Data used to characterize potential beach visitors were acquired from official statistics provided by the Statistical Institute of Catalonia (IDESCAT). The used indicator was the number of tourist accommodations (bed places) for each coastal municipality, which corresponds to the sum of the total number of bed places in hotels, cottages, and camping places. It is a proxy for the maximum number of potential tourists, and is used here to calculate the tourist BCC (see definition in Table 1). In order to put the tourism demand in context; 9.9 million tourists were registered within the coastal tourism brands during the summer season of 2015 (from June to September), with an average occupancy rate of 65%. Note that these data do not include tourists using unregulated lodging such as Airbnb.

2.2.3. Sea level rise

Tidal gauges with records going far enough back to estimate reliable current sea level rise along the Catalan coast are not available (e.g., Marcos and Tsimplis, 2008). Because of this, we have used average sea level rise for the Mediterranean to characterize current conditions. Gomis et al. (2012), reported that the mean sea level in the Mediterranean has been rising at a rate of 0.6 ± 0.1 mm/yr during the period 1948–2000, which is much lower than global rise in mean sea level during the period 1971–2010 (between 1.3 and 2.3 mm/yr, see Church et al., 2013). Marcos and Tsimplis (2008) calculated from the longest available records in the Mediterranean a rising sea-level trend between 1.2 and 1.5 mm/yr, although existing data are biased towards the North coast.

SLR projections are taken from the IPCC 5th Assessment Report (AR5), which are given by best-guess scenarios (50% probability level) for RCP4.5 and RCP8.5 (Church et al., 2013). In addition to this, we have also included a High-end scenario which has been taken from Jevrejeva et al. (2014) which accounts for uncertainties due to unknowns in polar ice-sheets processes (Antarctica and Greenland) and, it should be equivalent to the RCP8.5 with increased ice-sheet contribution (see also Jackson and Jevrejeva, 2016). For this study, we have used the upper bound given by the projection of sea level at 95% probability (see Jevrejeva et al., 2014). The inclusion of this High-end scenario has been done from the high risk-management perspective to characterize the system response and management requirements under very adverse conditions (e.g., Hinkel et al., 2015). These three scenarios are given by the year 2100 relative to 2000 by 0.53 m, 0.74 m and 1.75 m respectively (Fig. 3).

3. Methodology

The methodology for this study comprises the following steps: (i) development of the BCC evolution model; (ii) assessment of shoreline evolution and (iii) assessment of the evolution of BCC over time.

3.1. Beach-Carrying Capacity (BCC) model

This is a model of beach occupancy used to estimate the maximum number of beach users within an administrative unit. It depends on three main parameters: (i) the used beach surface or resting area (see definition in Table 1); (ii) the minimum surface per user; and (iii) the users' redistribution capacity within a given territory.

The first element determining the carrying capacity of a beach is the

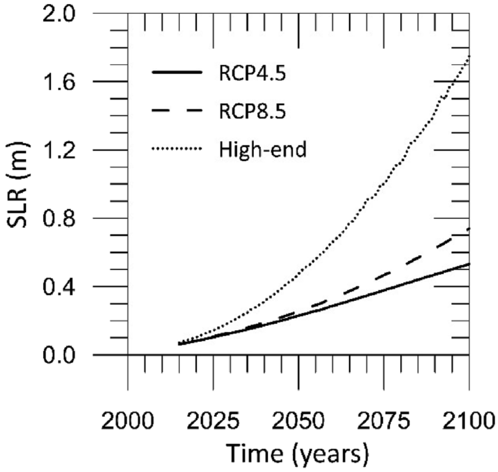

Fig. 3. SLR scenarios used in this study.

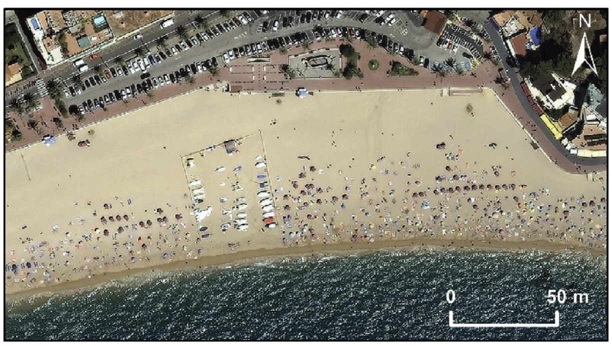

Fig. 4. Distribution of beach users across a wide beach in Costa Brava, showing the concentration near the shoreline.

model of occupation of the space by users. To this end, we use the concept of resting area (Table 1), which is the beach surface occupied by users that depends on the current beach width, the intensity of use, beach exploitation model and tidal conditions. In Spanish Mediterranean beaches, users tend to concentrate in a fringe close to the shoreline, the resting area; that although should ideally be as wide as necessary to comfortably accommodate users, in practice, users in Spanish Mediterranean beaches only concentrate in a 35 to 40 m-wide strip (Alemany, 1984; MOP, 1970; Valdemoro and Jiménez, 2006) (see Fig. 4). This area is not influenced by tides because it is a microtidal region (25 cm of tidal range). With this type of occupation model, the physical-carrying capacity (PCC) of beaches is given by the maximum number of users to be allocated within the resting area, in such a way that, in the case of eroding beaches but a with a resulting beach wider than the resting zone, BCC is not affected (see e.g. Valdemoro and Jiménez, 2006).

To calculate the final allowable number of potential users, it is necessary to consider the beach type that determines the typical density of use and the corresponding minimum beach surface per user. In this work we have used values characteristic of the area which are specified for each beach along the coast (see Table 2).

$$PCC = used\ beach\ area/\ minimum\ surface\ per\ user \quad (1)$$

Finally, once the carrying capacity is estimated for each beach, their values are integrated within a given management unit to assess the overall carrying capacity of the unit. This *spatial integration* is done assuming two conditions: (i) each beach maintains its typology and consequently, the allowed minimum surface per user; and (ii) users will redistribute across beaches within a given spatial unit to avoid exceeding the maximum user density. This implies a limitation of user mobility to the scale of integration, in such a way that they will only access beaches within the given spatial unit. This approach mimics the observed influence of distance between accommodations and the coastline on the behaviour of sun-and-sand tourists (e.g., García-Pozo et al., 2011; Pueyo-Ros et al., 2017). Thus, instead of considering alternative beaches for each accommodation within a given distance, we adopt a management-oriented approach in which we associate all accommodations within a given administrative unit with all beaches within such unit. In this study, the minimum integration scale is the municipality, and to simulate an increase in tourist mobility, it can be scaled up to the entire comarca, tourism region brand, or even the entire territory of Catalonia.

Based on these two conditions, the maximum number of beach users in a spatial unit is computed by integrating the capacity of all beaches within the unit but maintaining their individual minimum surface per user.

In order to differentiate the recreational use of the beach by tourists and local residents, results are expressed in terms of the percentage of their demand "served" by beaches within a given unit. Since this study is focused on the potential tourist demand, only the tourist BCC is computed (see Table 1). The tourist BCC is calculated for a given spatial integration unit as the ratio (in %) between the integrated PCC of all beaches within the unit and the maximum number of potential tourists of such unit, which is given by the integrated number of tourist accommodations (bed places).

3.2. Shoreline evolution

In this study, shoreline evolution rates for each beach are calculated under current conditions and under SLR scenarios. In order to calculate current evolution trends, shorelines were digitized at each beach along the Catalan coast from each available aerial photo. Extracted shorelines were estimated to have an average uncertainty of 2.5 m (CIIRC, 2008). Shoreline displacements were calculated at each beach along a series of control points, with an average spacing of 100 m. The decadal-scale shoreline rate of displacement was then computed by applying linear regression, a technique that removes short-term fluctuations and retains the long-term evolution trend (Dolan et al., 1991). This evolution trend integrates the contribution of all forcing conditions acting on the coast. Since it covers a 20-year period, it can be considered as representative of most probable conditions, from storm to fair-weather-wave states. Each beach was characterized by an integrated shoreline rate of displacement, which was computed by averaging values computed for all control points along the beach. This analysis was done by using the ArcGIS tool "Digital Shoreline Analysis System" (DSAS), v. 4.3 (Thieler et al., 2009).

It has to be noted that the so-obtained evolution rates are used as an empiric model to make shoreline projections under current conditions. The underlying assumption is that no significant changes are affecting littoral dynamics and coastline evolution. This implies that no significant changes in natural conditions will occur (e.g., river sediment supplies, wave climate) and that the current management practices will be maintained.

To calculate the SLR-induced shoreline retreat, we have followed Jiménez et al. (2017), who used the Bruun model. This simple model assumes that the beach profile adapts to the SLR though an upward and landward displacement of the active profile, maintaining the shoreline shape and relative elevation with respect to the new water level (Bruun, 1962). Although some authors question the general validity of this model (e.g., Cooper and Pilkey, 2004), in the absence of a generally-accepted morphological model, it is widely used (e.g., Le Cozannet et al., 2014). Additionally, it provides an indicative estimate of expected shoreline retreat at the regional scale. The induced shoreline retreat, ΔX, is given by the Eq. (2) where ΔMWL is the sea-level rise, B is the berm/dune height of the active beach, d_* is the active depth (or depth of closure), L is the across-shore distance from B to d_*, and *Sact* is

Table 3
Sections along the Catalan coast (and corresponding *comarcas*) based on the slope of the inner shelf (down to 10 m water depth).

Coastal section	Coastal comarca	Inner shelf slope
Costa Brava	Alt Empordà (1)	1/87.5
	Baix Empordà (2)	
	Selva (3)	
Maresme	Maresme (4)	1/75
	Barcelonès (5)	
LLobregat	Baix Llobregat (6)	1/100
Costa Dorada	Garraf (7)	
	Baix Penedés (8)	
	Tarragonés (9)	
	Baix Camp (10)	

the averaged inner shelf slope over which the beach profile changes. Ranasinge and Stive (2009) identify the selection of a closure depth representative of this time scale as one of the sources of uncertainties to apply this model. In this work, to overcome this, we adopt the approach of Jiménez et al. (2017), who applied Eq. (2) at the regional scale by selecting coastal stretches with an alongshore, homogeneous, inner-shelf slope. This slope has been calculated from the shoreline to 10 m water depth and, thus extending deeper than the medium-term closure depth of the area that has been calculated as about 7 m (CIIRC, 2010). Table 3 shows the representative inner shelf slopes used in the different sectors along the Catalan coast. Obtained SLR-induced shoreline retreats are then considered to be constant for all beaches within a given coastal stretch.

$$\Delta X = \Delta MWL \frac{L}{(B + d*)} \approx \frac{\Delta MWL}{Sact} \tag{2}$$

3.3. Time evolution of BCC

To assess the BCC temporal evolution along the Catalan coast, we have projected PCC to each selected time horizon by using different scenarios: (i) current conditions, and (ii) assuming an acceleration of SLR according to selected projections.

In the first case, computed shoreline rates of displacement have been extrapolated to the selected time horizon to forecast future beach widths. Hence, we are assuming that no significant changes in governing conditions for coastal dynamics along the Catalan coast will occur over the considered period. Regarding this, it should be noted that existing wave projections for the area over the next century do not show any increase in storminess, and detected changes in mean wave conditions when translated to coastal sediment transport and potential changes in coastline evolution have a high degree of uncertainty (e.g., Casas-Prat et al., 2016).

In the second case, the contribution of climate change to BCC evolution was considered by adding the estimated SLR-induced erosion under each scenario to the estimated baseline shoreline rates of displacement. However, since current projected shoreline evolution rates integrate all acting processes during the 1995–2015 period, they also should include the contribution of the current SLR. Therefore, the Bruun rule was applied to estimate the contribution of current SLR to shoreline erosion during the last 20 years, and was subtracted from evolution rates to obtain the non-SLR contribution. This component is then added to SLR-induced erosion under selected climatic scenarios.

4. Results

4.1. Shoreline evolution

The statistical distribution of shoreline evolution rates under current conditions for beaches along the Catalan coast is shown in Fig. 5. Obtained values are biased towards negative values, reflecting a dominant erosive decadal-scale behaviour during the analysed period (about 65% of the beach length is retreating) at an average rate of displacement of −0.4 m/y. As Jiménez and Valdemoro (2019) pointed, this erosive behaviour is reflecting the integrated effects of natural dynamics and human influence in the territory. Main human forcings are related to variations in sediment supply to beaches and perturbations in sediment transport patterns due to coastal works, with special influence of existing marinas. In fact, largest shoreline displacement rates (both negative and positive) showed in Fig. 5, correspond to sites largely affected by the presence of obstacles locally modifying littoral dynamics such as in the surrounding of marinas along the Maresme coast (see also Ballesteros et al., 2018), and to hotspots in deltaic areas suffering of river sediment input decrease (Jiménez et al., 2018; Rodríguez-Santalla and Somoza, 2019).

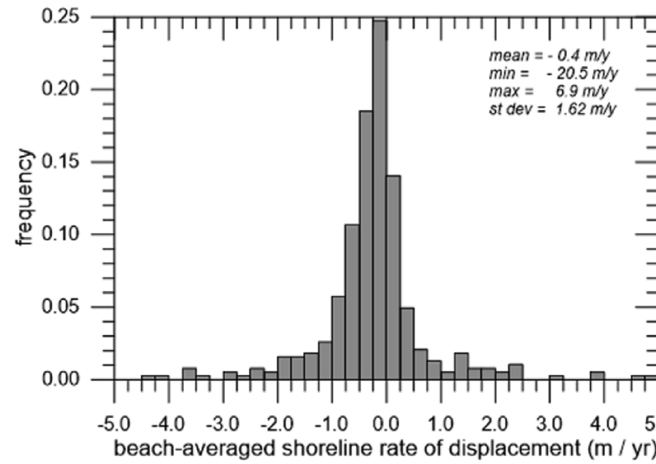

Fig. 5. Histogram of beach-averaged shoreline evolution rates during the 1995–2015 period along the Catalan coast.

These calculated evolution rates are the integrated result of natural littoral dynamics and human action on the coast during the analysed period. Thus, it has to be considered that during this period; about 5 millions of m^3 of sand have been supplied to the Catalan coast to try to mitigate local stability problems (see Jiménez and Valdemoro, 2019). This implies that the natural background erosion rate should be higher than the calculated one, with the "excess" of erosion being equivalent to that required to remove the supplied volume. In a recent study on the performance of nourishment operations along the southern part of the Catalan coast (Tarragona province) during the last 20 years, Galofré et al. (2018) evaluated this excess of erosion about −0.1 m/y.

Fig. 6 shows the SLR-induced shoreline retreat of a representative part (comarcas 6 to 10) of the Catalan coast for the SLR scenarios. As can be seen, the average SLR-induced retreat is projected to be almost the same in 2050 for RCP4.5 and RCP8.5 scenarios (around 20 m), whereas they significantly differ by 2100 due to the expected acceleration in sea level rise under RCP8.5 (47 m and 66 m for RCP4.5 and RCP8.5, respectively). For the high-end scenario, the calculated retreat is about two times larger than those associated with other RCP scenarios in 2050 and three times larger in 2100 (see also Jiménez et al., 2017). Table 4 shows the estimated shoreline SLR-induced retreats to be applied to each sector along the coast.

4.2. Physical-carrying capacity (PCC)

At present, beaches along the coast can accommodate up to maximum of about 1.37 million users at one time (excluding the Ebro delta beaches). They present a non-homogeneous distribution per comarca that reflect the dominant geomorphology and extension of each unit.

The PCC distribution aggregated per tourism brand is shown in Table 5. As can be seen, the two most well-known Catalan tourism

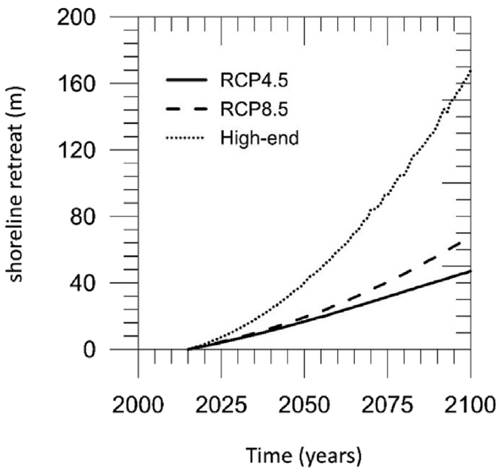

Fig. 6. SLR-induced shoreline retreat for the southern comarcas (6–10 in Tables 1 and 3) of the Catalan coast under selected SLR scenarios.

Table 4
Shoreline retreat (m) under different SLR scenarios in 2050, 2075, and 2100. The values are referenced to 2015 measurements.

Coastal comarcas	Shoreline retreat (m)			
	SLR scenario	2050	2075	2100
1, 2, 3	RCP 4.5	15	28	41
	RCP 8.5	17	35	59
	H. E.	35	81	147
4, 5	RCP 4.5	13	24	35
	RCP 8.5	14	30	51
	H. E.	30	70	126
6, 7, 8, 9, 10	RCP 4.5	17	32	47
	RCP 8.5	19	41	68
	H. E.	40	93	168

brands, Costa Brava in the north and Costa Dorada in the south, comprise about 60% of the total PCC, whereas they comprise 67% of the tourist bed places. The largest PCC is provided by the Costa de Barcelona brand, which includes the comarca with the highest number of users (272,000), Maresme, which is composed of a 42 km-long sandy coastline. In spite of being the brand with the largest PCC (34% of the total), it only provides 16% of total tourist accommodations. Finally, the city of Barcelona, the area with the highest tourist affluence, only supports 6% of the PCC.

PCC projections along the analysed coast show a decrease for all areas, although with significant spatial variation. Thus, considering the expected changes by 2050 under current conditions, the total PCC of the analysed beaches will decrease down to 81% of the current capacity (1.108 million users). Observed spatial variability is due to the combination of variations in coastline evolution and beach morphology. The least affected brand will be Costa Brava, which will maintain 89% of the present PCC (392,000 users in 2015, Table 5). This is due to its geomorphology characterized by bay beaches within headlands having relatively low erosion rates. On the other hand, Costa de Barcelona is the most affected tourism brand, where PCC decreases to 77% of the current capacity. This area includes the Maresme comarca, which has the largest shoreline erosion rates along the Catalan coast (excluding Ebro delta beaches).

The total PCC by 2050 under the RCP8.5 scenario will decrease to 64% of the present capacity (880,000 users, Table 5). Although this value is similar to that predicted under the influence of current coastal processes, the observed spatial variability is quite different, with all zones presenting similar reduction rates. In comparison with the previous scenario, the Costa Brava will be one of the most affected brands, maintaining 68% of present PCC. On the other hand, the PCC of Maresme beaches will be reduced down to 54% of actual values, which represents a 10% increase with respect to current climatic conditions. For the other tested scenarios, PCC will also experience the same decreasing trend which is proportional to SLR. Thus, in 2050, the total PCC will be 916,000 users under RCP4.5 and 616,500 users under the high-end scenario. These reductions will significantly increase beyond 2050 due to the expected SLR acceleration under tested scenarios.

4.3. Tourist BCC

Fig. 7 shows the BCC integrated at the municipality and comarca scales versus potential users (tourists). At present, when the tourist BCC is integrated at the municipal scale (Fig. 7a), beaches are able to absorb between 80 and 100% of the potential demand. There are three locations lacking sufficient space to accommodate the potential maximum demand: Santa Cristina d'Aro (Baix Empordà), Barcelona (Barcelonès) and Cubelles (Garraf), which only satisfy 17%, 59%, and 61% of the local demand, respectively. However, if the spatial integration is enlarged up to the comarca level, which implies that users can be redistributed to all beaches within a given comarca, all regions will satisfy the potential maximum tourist demand (Fig. 7b). It has to be considered that the change in the scale of the spatial aggregation will reflect the maximum distance to be covered by users to visit a beach from their place of lodging.

As expected, the percentage of tourism demand satisfied by beaches will decrease with time and with the magnitude of sea level rise. As an example, in 2050 and under current climate conditions, the number of municipalities with insufficient beach surface to support 100% of the tourist BCC will increase from 3 to 10. In fact, if no adaptation action is taken, some beaches will disappear and the expected tourist BCC for some municipalities will become nil (e.g., Caldes d'Estrac and Cabrera de Mar in Maresme) (Fig. 7a). When the effect of different SLR scenarios is considered, the number of significantly-affected municipalities increases (Fig. 7a). Thus, for the RCP8.5 scenario, 10 municipalities will present low or very low tourist BCC, increasing to 23 under the high-end scenario. It should be noted that severely affected municipalities are different than those identified under current conditions, with most of them being located in the Costa Brava (Cadaqués, Palafrugell, and Blanes) (Fig. 7a). When the analysis is at the comarca level, the tourist BCC reduction is smoothed out due to the potential redistribution of beach users within a larger unit. La Selva is the only affected comarca with decreases to 40% of the current tourist under BCC RCP8.5 scenario

Table 5
Characteristics and PCC for the different tourism brands along the Catalan coast.

Tourism brand	Comarca	Beach length (km)	Tourist accommodation (bed places in thousands)	PCC - thousands of users – (percentage over total)		
				Reference 2015	2050 (current climate)	2050 (RCP8.5)
Costa Brava	1, 2, 3	54.33	179.44	392 (29%)	347 (31%)	267 (30%)
Costa de Barcelona	4, 6, 7	63.91	72.02	471 (34%)	363 (33%)	305 (35%)
Barcelona city	5	12.88	73.54	82 (6%)	64 (6%)	50 (6%)
Costa Dorada	8,9,10	57.34	112.54	421 (31%)	334 (30%)	257 (29%)
Total			**437.54**	**1366**	**1108**	**880**

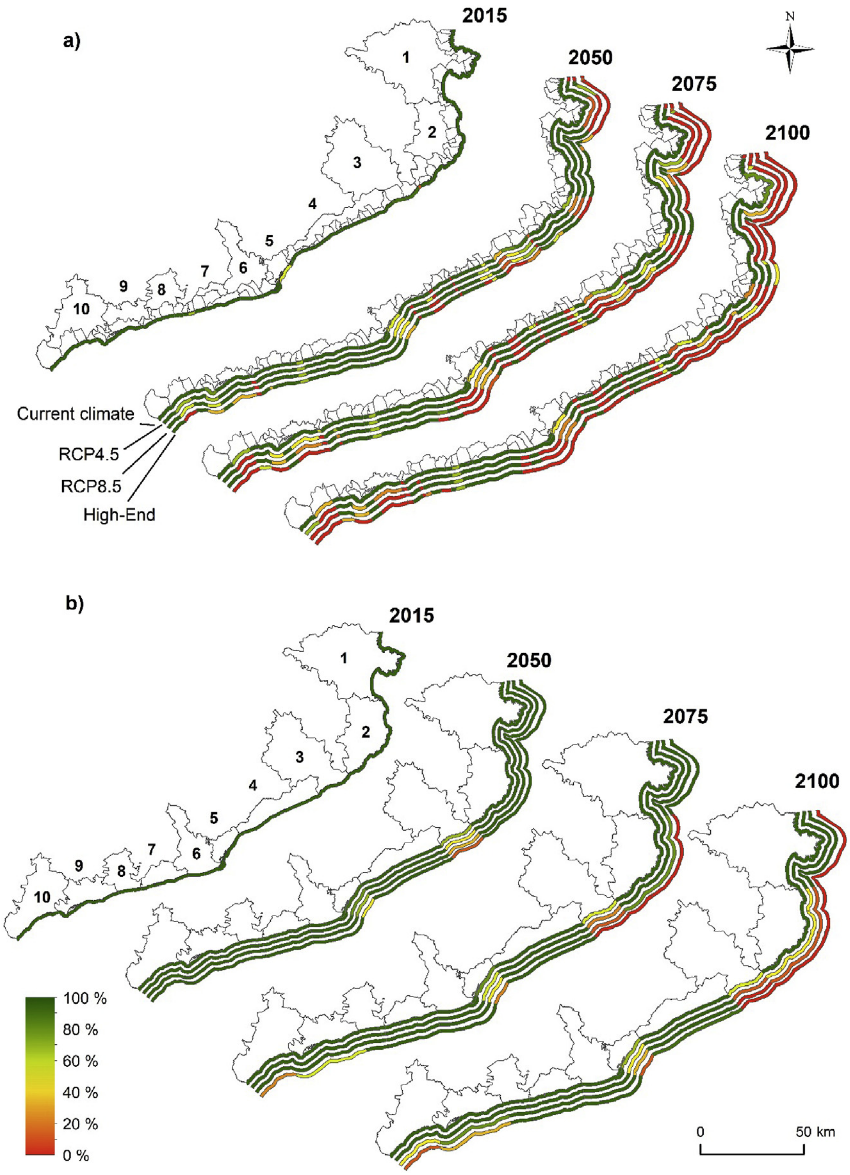

Fig. 7. Tourist BCC integrated at the (a) municipal level, and (b) comarca level.

(Fig. 7b).

When the analysis is extended to 2100, a dramatic decrease in tourist BCC is expected, especially for RCP8.5 and the High-End scenarios (Fig. 7a and b). Under the RCP8.5 scenario, the tourist BCC for about half of the coastal municipalities will decrease to less than 20% of present values (Fig. 7a). If values are integrated at the comarca level, a smaller effect on the tourist BCC is observed. However, some comarcas experience a significant reduction; with La Selva (Costa Brava) being most affected as it will only be able to provide 2% of the required tourist BCC in 2100. Other significantly affected areas are Baix Camp and Tarragona (Costa Dorada), which will be able to provide 48% and 78% of the required BCC, respectively, and Barcelonès (city of Barcelona) and Baix Empordá (Costa Brava) with 38% and 19%, respectively (Fig. 7b).

5. Discussion and conclusions

5.1. Methodological aspects

A methodology to assess the evolution of the recreational capacity of beaches at different management scales as a function of coastline evolution is proposed and applied to Catalan beaches under different climate scenarios. In this sense, this research belongs to the category of quantitative approaches to evaluating the effects of climate change on tourism based on a consideration of physical changes (Roselló-Nadal, 2014). Most existing analyses on the potential effects of climate change on sustainability of coastal tourist destinations focus on potential changes in climatic attractiveness (e.g., Amelung and Viner, 2006; Moreno and Amelung, 2009b; Perry, 2006, among others). However, in addition to climate conditions, beaches are the main resource for sustaining tourism in most coastal destinations, such as the Mediterranean countries, and any impact on the quantity and quality of beaches will affect tourism. In a business scenario, in which the success of every season is usually indicated in terms of the percentage of increase in incoming tourists, any sustainable long-term planning requires an assessment of the evolution of the main resource to be "exploited", the beach. In this context, the evolution of the available beach surface area will determine the potential maximum number of users that can be served as well as the user density, the latter aspect being an important issue in influencing the user perception of beach quality (e.g., Ariza et al., 2010; Roca et al., 2008; Rodella et al., 2017).

With respect to this, Valdemoro and Jiménez (2016) among others

have formalized the relationship between shoreline dynamics and beach user density. Thus, the inclusion of long-term erosion rates emerges as a key factor to estimate future beach carrying capacity under current conditions (*i.e.*, Alexandrakis et al., 2015; Rodella et al., 2017; Silva et al., 2007; Zacarias et al., 2011). On the other hand, climate change projections have determined the need to assess SLR-induced changes in carrying capacity (e.g., De Sousa et al., 2018; Jiménez et al., 2017; Scott et al., 2012; Toimil et al., 2018). In this work, we have compared the contribution of each component of shoreline evolution to future carrying capacity variations and, have combined both to assess their integrated effect. This is important since when designing management responses to this future threat, such as nourishment volumes to maintain beaches (e.g., Hinkel et al., 2013), we have also to consider needs under current conditions which will have to be added to the so-estimated volumes to assess the existence of enough resources (e.g., Jiménez et al., 2011, 2017).

While SLR-induced erosion is an indisputable hazard to be included in any long-term assessment, there is much less agreement on how to properly assess it. Thus, in spite that the Bruun rule is probably the most used methods to predict shoreline retreat (e.g. Le Cozannet et al., 2014), there is a disagreement about its validity (see e.g., Cooper and Pilkey, 2004). In consequence, there have been different attempts to modify, reformulate or propose new models (e.g., Ranasinge et al., 2012; Rosati et al., 2013; Taborda and Ribeiro, 2015). However, these models also present the same shortcoming than the Bruun rule, *i.e.* they have been hardly verified and/or validated and, in this sense, they also have an inherent uncertainty. One of the problems to select a reliable method is the lack of adequate data for validation due to the hypothesis done by models and, in consequence, the limitation of existing data fulfilling such conditions (see e.g., Le Cozannet et al., 2016; Zhang et al., 2004). Recently, some works have addressed model validation using laboratory experiments (e.g., Atkinson et al., 2018; Beuzen et al., 2018; Monioudi et al., 2017), although still they are limited in quantity and need to be completed to perform a robust validation of existing models. Within this context in which no universally accepted model exists, we have selected to use the Bruun rule to estimate SLR-induced shoreline retreat. To this end, we have applied it by following recommendations of Stive et al. (2009) who suggested using it for regional scale assessments. In this sense, we do not apply the model at the beach scale, but we use to obtain regional scale SLR-induced background erosion. In this case, as we mentioned in the methodology section, we have divided the Catalan coast in three zones in terms of the inner shelf slope and we obtain a representative background erosion rate for each zone. This rate is later applied to each beach, with the corresponding time-response being the combination of such regional erosion rate and the local beach width. It has to be also noted that here we are assuming that no changes in sediment sources/sinks along the coast are considered (see e.g., Jiménez et al., 2017).

In this study we assume a model of use of the beach space and defined maximum-use density values, based on local characteristics. Both elements can be modified to adapt to sites with different spatial distribution of users or, to test how BCC would vary under different management scenarios, such as accepting a higher density of users. Therefore, this simple, flexible, and easy-to-use beach-user interaction model can be adapted to physical changes as well as to modifications in the beach management model.

One of the advantages of the adopted approach is that we have defined a model of use of the beach space, including saturation density values based on local characteristics. Therefore, each beach is classified in terms of its current use characteristics and, thus, the SLR-induced beach width decrease will have a differentiated impact on BCC. This approach permits to assess the impact on regional BCC by changing local beach management, as it would be the case of modifying accepted saturation levels. In our case study, we have assigned different intensity of use and saturation levels values using existing databases where all beaches were previously classified in terms of these two variables. In the case of non-existence of such information, the same procedure could be applied by assigning different saturation values as a function of their typology (e.g., urban, semiurban, natural).

One of the management-oriented key points of the model is the spatial integration of the BCC. The adopted approach integrates the carrying capacity from a basic unit, the beach, up to a given spatial (management-oriented) unit such as the municipality. This model assumes that the maximum level of mobility of tourists is determined by the integration scale, in such a way that beaches within a given management unit are only serving tourists staying in such unit. This has two main implications: (i) first, from the managerial standpoint, BCC is assessed as an integrated variable accounting for all beaches within a given management (integration) unit; and (ii) second, the implicit consequence is that if all beaches within a given unit lack of sufficient carrying capacity, tourists will change their destination, *i.e.,* they will move on to a different municipality or brand providing sufficient BCC. In this sense, the developed methodology allows assessing the capacity to accommodate the maximum potential number of tourists in the territory by redistributing the demand over different spatial units. This should facilitate exploring the formulation of adaptation measures based on the management of the accommodation offer along the territory taking into account the spatial distribution of future BCCs.

The tourist sector is here indicated by means of the maximum number of potential visitors derived from the total number of tourist bed places. However, it has to be considered that this number does not include people using accommodations that are not reflected in official statistics, such as accommodation-sharing sites, second-home residences, or day-visitors from outside the management unit. As an indicator of the potential capacity associated with this "uncontrolled" component, the report on the 2017 summer tourist balance in Catalonia (Generalitat de Catalunya, 2017) estimates that the housing for the tourist-use component offers about 35% of total bed places. This implies a "best-case scenario" impact assessment, since the maximum potential total tourist demand would be larger than that considered here. The use of bed places to compare with the BCC implies the assumption of full occupancy. To put into context the obtained results, the above-mentioned report (Generalitat de Catalunya, 2017) stated that the occupation rate during the 2017 summer season (June to September) in hotels in the analysed coastal tourism brands was about 83%. In the analysis presented here we have assumed that the offer of tourist accommodations within a spatial unit will not change with time. This is not a requirement of the model, which can be modified to take into account any time variation in the beach demand, including scenarios of growing tourism sector.

5.2. Temporal and spatial changes in BCC

The results indicate that at *present*, beaches along the Catalan coast (excluding the southernmost comarcas comprising the Ebro delta) can accommodate a maximum of about 1.366 million beachgoers under the current model of use (use of the available space and maximum allowable user density for each beach). This overall capacity is larger than the total number of tourist bed places and it should indicate that at present, Catalan beaches have the capacity to accommodate the maximum potential tourist demand. However, if we impose a limitation in tourist mobility, which is here modelled through the spatial integration of BCC, to the municipality scale, beaches along the Catalan coast are able to accommodate up to 89% of the maximum potential tourist demand without changing current beach management. Barcelona is one of the most affected municipalities, with beaches providing 59% of its tourist BCC due to the large number of tourists. However, this quantity of tourists is not directly linked to beaches since Barcelona is not the classical sun-and-sand destination. To put the obtained results in context, according to the Barcelona municipality, the influx of users to Barcelona beaches during 2016 was about 4.7 million, and the average used surface per visitant was estimated in about 7 m^2/user, with some

beaches having values lower than 4 m^2/user (Ajuntament de Barcelona, 2017). In any case, it should be considered that the degree of occupation of these beaches presents significant time variations such that the same beach can range from situations of low occupation to saturation (e.g., Guillén et al., 2008). In order to properly interpret overall results, it has to be considered that at present, there are municipalities along the Catalan coast which are able to support 100% of the current tourist demand, which at the same time, present singular user density values close to or above saturation levels at some beaches (e.g., Roca et al., 2008; Sardá et al., 2009).

As it was already mentioned, beach width projection under current conditions have been estimated assuming that current natural and management conditions will not vary during the projection time. Thus, any potential change in current shoreline management options should affect future shoreline evolution and BCC even assuming no change in climate conditions. To assess the potential magnitude of such changes, if current maintenance beach nourishments performed during the last years, this would imply an increase of −0.1 m/y in the average background shoreline retreat rate.

Projection of present shoreline trends along the Catalan coast to 2050 indicates a 19% decrease in the overall PCC under current dynamic conditions, which would increase under a highly-probable climate change due to the estimated SLR-induced erosion up to 33%, 36%, and 55% for RCP4.5, RCP8.5 and high-end scenarios, respectively. When these figures are put in the context of potential implications for tourism, even in the absence of climate change, some municipalities will experience a measureable decrease in tourist BCC such that beaches will only be able to accommodate 83% of the maximum potential tourist demand if no actions are taken to manage them. Future tourist BCC perspectives will be much worse for the case in which climate change-induced effects are considered, with the capacity to absorb the maximum potential tourist demand being 74%, 72%, and 53% for RCP4.5, RCP8.5 and high-end scenarios, respectively. It should be considered that this decrease in tourist BCC is not evenly-distributed along the Catalan coast. It is mainly concentrated in municipalities in the North (Costa Brava), where the number of potential tourists is very high and beaches are relatively narrow (Fig. 7a).

For longer-term projections, this behaviour is reinforced and extended along the entire Catalan coast. Thus, for instance, under the RCP8.5 scenario, the overall tourist BCC will be 51% and 34% of the current maximum potential tourist demand in 2075 and 2100, respectively (Fig. 7a).

However, if we increase the aggregation scale up to the comarca level, the excess of users above saturation levels is redistributed among all beaches within a larger spatial unit. This indicates that the coastal system has the capacity to better absorb the overall demand (Fig. 7b) following a redistribution of users across the territory. It should be noted that the scales of aggregation have been selected in accordance with the administration structure in Spain, but since the information is individually obtained for each beach, the integration can be carried out at any spatial scale. As a rule of thumb, results show an increasing number of tourist BCC hotspots as the territorial unit becomes smaller. Consequently, this analysis between different integration scales could be useful in order to define more optimum management scales, and to locate hotspots and priority areas in order to define an adaptation strategy focused on sustaining the recreational use of beaches.

Regarding the tourist BCC hotspots identified here, the results indicate that the expected capacity to absorb the tourist demand of beach space of a given quality will be significantly affected by climate change if measures to avoid the BCC loss are not adopted. One of the most potentially-affected brands will be the city of Barcelona, although from the standpoint of tourism, this destination has other multiple tourist attractions, such as culture, architecture, and gastronomy. Regarding the most well-known coastal tourism brands, Costa Brava and Costa Dorada, both have municipalities that would be severely affected over long-time scenarios (to 2100), losing 87% and 53% of their current tourist BCC, respectively under RCP8.5.

Although beaches are used by both tourists and the local population, here we have focused exclusively on the tourist sector. In this sense, the estimated impact would be a “best-case scenario,” because if we also account for the use of beaches by the local population, the available surface will be further reduced. In this sense, data on beachgoer's origin obtained in different beaches in the Costa Brava area indicate a percentage of locals of about 20–30% (Lozoya et al., 2014; Roca et al., 2008). This percentage of beach use by locals would increase in areas with low tourism and high population density, such as Maresme south, the metropolitan coast northwards of Barcelona (Ballesteros et al., 2018). To get an order of magnitude of this effect, assuming that on average, 25% of beach users are of local origin, the overall tourist BCC integrated at the municipal scale for the area of study under RCP8.5 scenario will be 65%, 45%, and 31% of the current maximum potential tourist demand in 2050, 2075, and 2100, respectively.

The results show the high sensitivity of the coastal tourism sector to climate change not only as a function of the change in climatic conditions controlling comfort, but in terms of time variations in the primary resource to be exploited, *i.e.*, the beach. The assessment presented has been done for a scenario of constant-over-time tourist accommodation capacity and consequently, constant potential beach demand by tourists. In this sense, this can be considered a best-case scenario which could be refined by testing different scenarios of time-evolution of tourists, including government aspirations for the tourist industry.

5.3. Management implications

In all cases, these results indicate that to maintain the economic contribution of the tourist sector, efficient adaptation measures are required. The aim of these measures should be to maintain future beach carrying capacity within a given range in order to properly support beach demand. This could be done or by (1) redistributing users along the coast, (2) increasing the density of use, (3) increasing the beach surface, or (4) combining some of them. Regarding the option 1, this strategy would not likely be implemented at a regional scale, since it implies “abandoning” well-established areas with local economies strongly linked to tourism (e.g., Costa Brava). However, from a local standpoint, this could be an opportunity for less-developed areas, which could offer new accommodation units in areas with enough BCC. Option 2 would imply a decrease in beach quality with the corresponding effects on users. Since many of the beaches analysed here are urban ones in which the accepted saturation level is high, the increase in density for these beaches would lead to a situation of permanent overcrowding. In the remaining beaches, the increase in user density implies that in effective terms, they will change from semi-urban and natural beaches to urban-like ones. Finally, the management of BCC through the conservation of available beach surface requires the implementation of traditional, coastal engineering measures to reduce and/or to compensate erosion. Along the Catalan coast, this has been the traditional way of mitigating erosion problems, such that during the last 30 years, more than 25 million m^3 of sand nourishment have been deposited on Catalan beaches (e.g., Jiménez and Valdemoro, 2019). In spite of this nourishment strategy, Catalan beaches present an erosive behaviour, which will be exacerbated under SLR. Consequently, the implementation of an adaptation strategy based exclusively on beach nourishment requires having a strategic sediment reservoir with enough quality sediment to maintain future beach widths. However, current estimates of existing nearshore sediment stocks are insufficient to cover expected needs (e.g., Galofré et al., 2018) unless new sand stocks are found. A possible approach to overcoming this limitation in existing resources will be to concentrate adaptation measures in high-priority areas identified with this analysis, where future beach evolution will result in a significant decrease in tourist BCC.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ocecoaman.2018.12.028.

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